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(54) **RADIATION DETECTOR HAVING A BANDGAP ENGINEERED ABSORBER**

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(51) **Int. Cl.**

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H01L 31/18	(2006.01)
H01L 31/0296	(2006.01)
H01L 31/103	(2006.01)
H01L 31/0216	(2014.01)

(52) **U.S. Cl.**

CPC ***H01L 31/1832*** (2013.01); ***H01L 31/02161*** (2013.01); ***H01L 31/02966*** (2013.01); ***H01L 31/1032*** (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,009,180	B2	3/2006	Sterling et al.	
2002/0020859	A1	2/2002	Muramatsu	
2007/0285538	A1	12/2007	Suzuki	
2009/0121307	A1 *	5/2009	Tennant	257/440

OTHER PUBLICATIONS

Beck, J., et al., "The HgCdTe Electron Avalanche Photodiode", Journal of Electronic Materials, vol. 35, No. 6, 2006, pp. 1166-1173.

(Continued)

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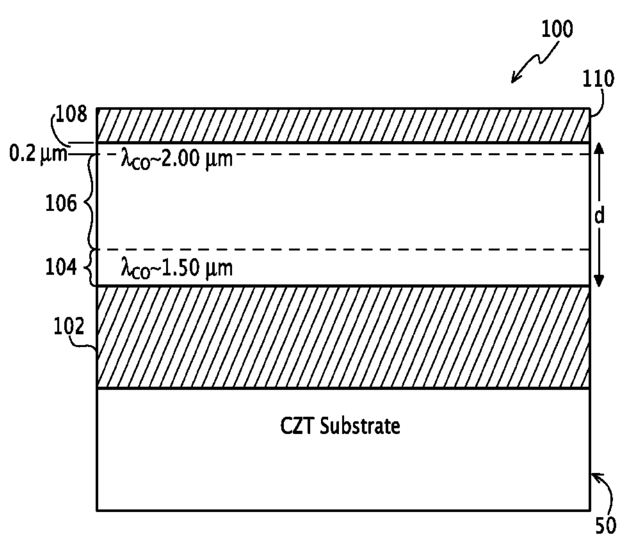
(57) **ABSTRACT**

A radiation detector is provided that includes a photodiode having a radiation absorber with a graded multilayer structure. Each layer of the absorber is formed from a semiconductor material, such as HgCdTe. A first of the layers is formed to have a first predetermined wavelength cutoff. A second of the layers is disposed over the first layer and beneath the first surface of the absorber through which radiation is received. The second layer has a graded composition structure of the semiconductor material such that the wavelength cutoff of the second layer varies from a second predetermined wavelength cutoff to the first predetermined wavelength cutoff such that the second layer has a progressively smaller bandgap than the first bandgap of the first layer. The graded multilayer radiation absorber structure enables carriers to flow toward a conductor that is used for measuring the radiation being sensed by the radiation absorber.

20 Claims, 8 Drawing Sheets



(56) **References Cited**

OTHER PUBLICATIONS

Beck, J., et al., "The HgCdTe Electron Avalanche Photodiode", IEEE LEOS Newsletter, Oct. 2006, pp. 8-12.

Non-Final Office Action mailed Nov. 5, 2012 in U.S. Appl. No. 12/853,174, 9 pages.

Final Office Action mailed Nov. 1, 2013 in U.S. Appl. No. 12/853,174, 10 pages.

* cited by examiner

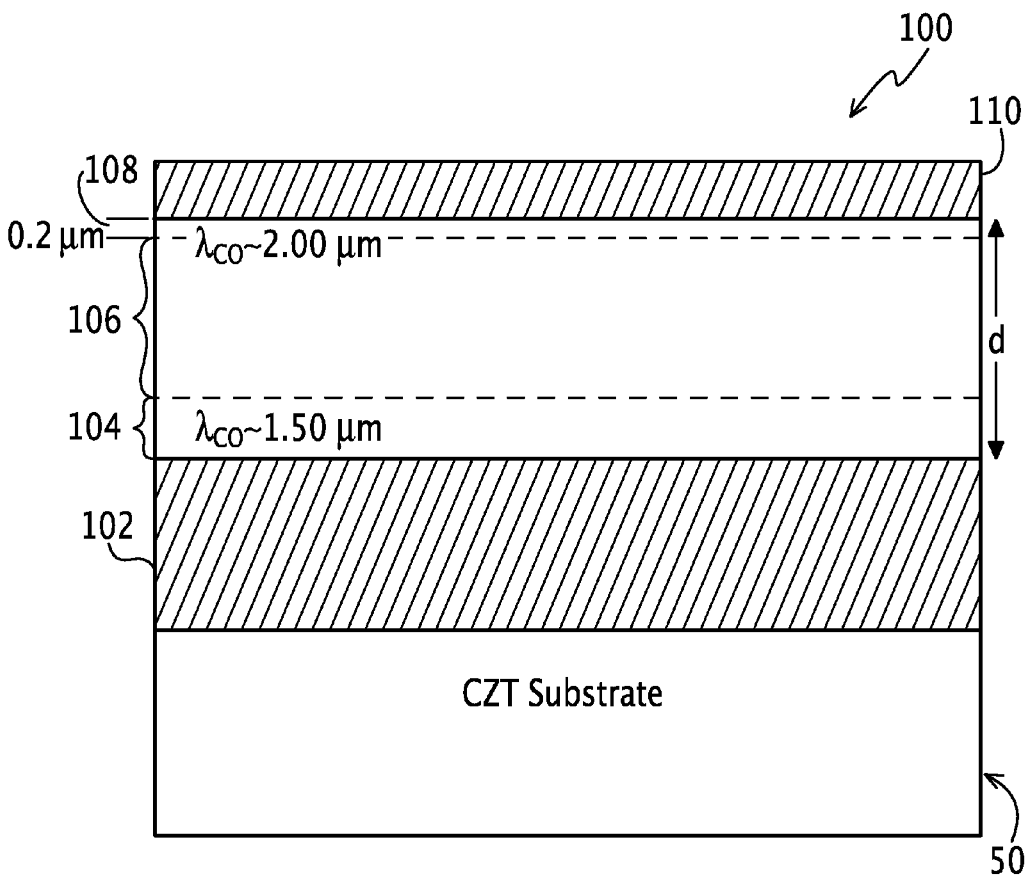

100
110
108
0.2 μm
λ_{CO}~2.00 μm
106
d
104
λ_{CO}~1.50 μm
102
CZT Substrate
50

Fig. 1

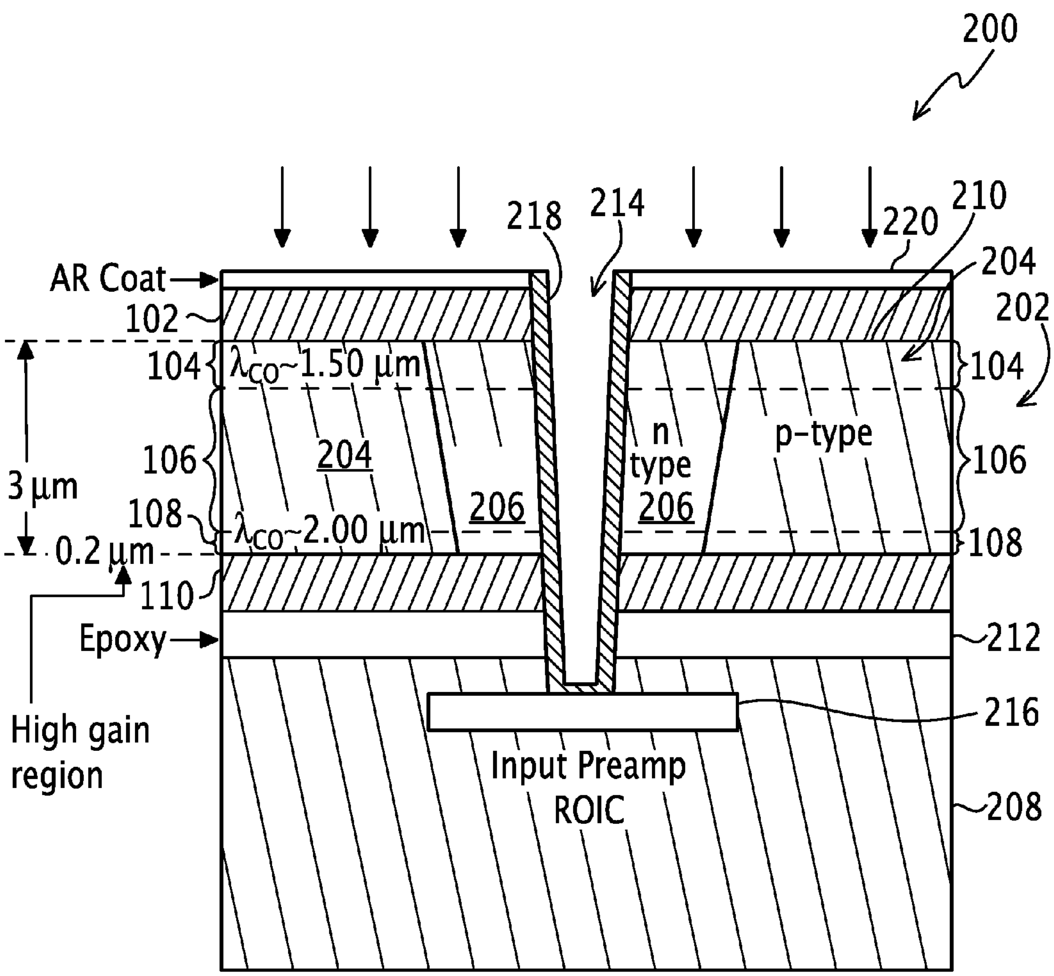

200
218
214
220
210
204
202
AR Coat
102
104
λ_{CO}~1.50 µm
104
106
204
206
n
type
206
p-type
106
3 µm
108
λ_{CO}~2.00 µm
108
0.2 µm
110
Epoxy
212
216
High gain
region
Input Preamp
ROIC
208

Fig. 2

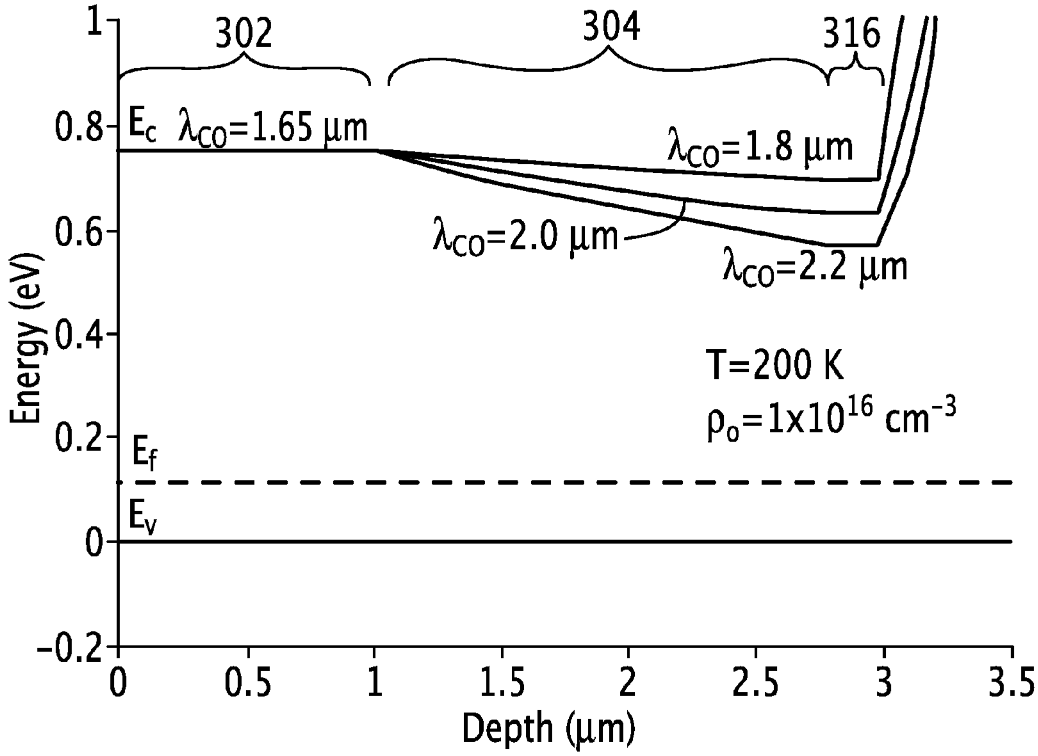

302
304
316
E_c
λ_{CO}=1.65 μm
λ_{CO}=1.8 μm
λ_{CO}=2.0 μm
λ_{CO}=2.2 μm
T=200 K
ρ_o=1x10^{16} cm^{-3}
E_f
E_v
Energy (eV)
Depth (μm)
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
2.5
3
3.5

Fig. 3

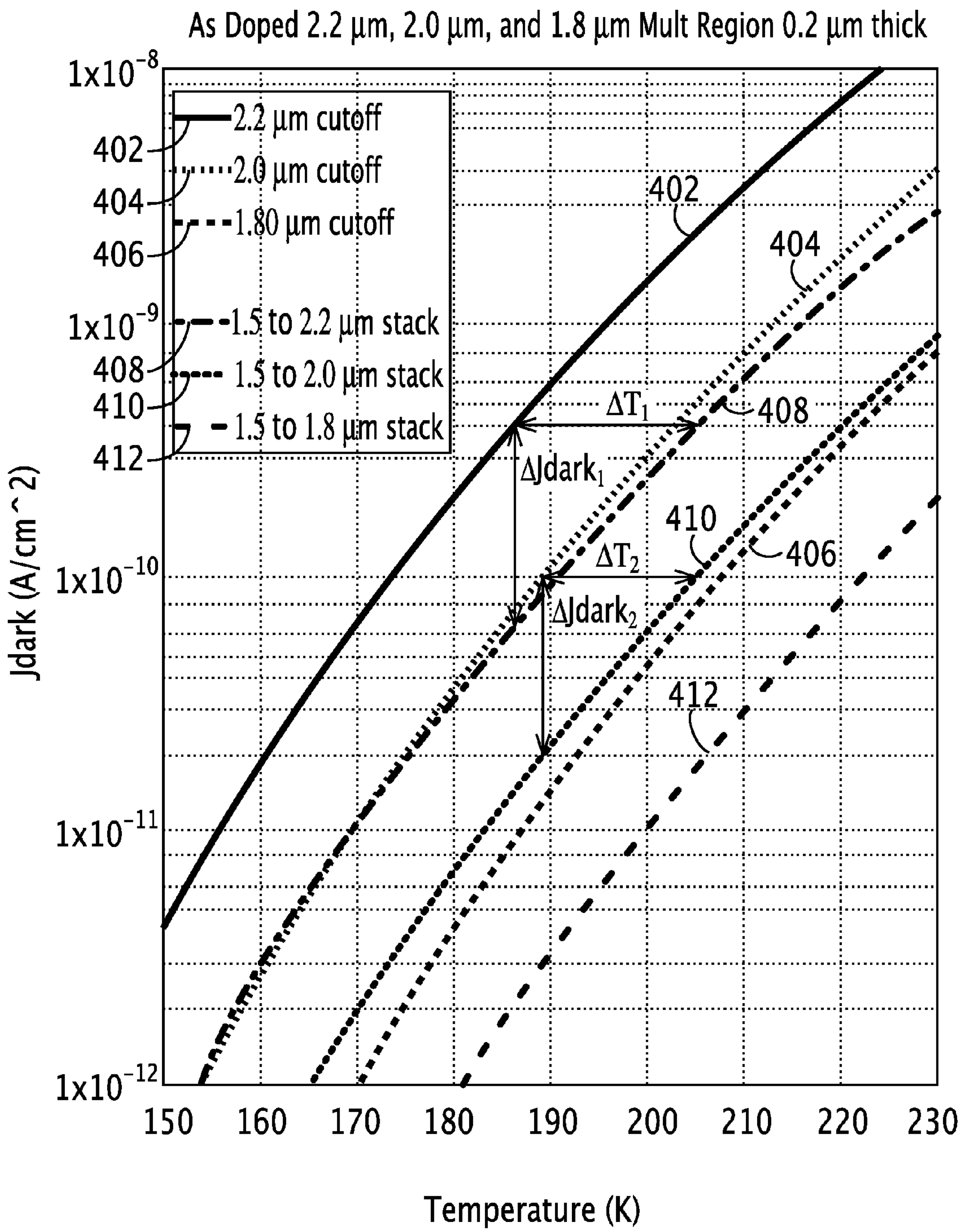

As Doped 2.2 µm, 2.0 µm, and 1.8 µm Mult Region 0.2 µm thick
2.2 µm cutoff
2.0 µm cutoff
1.80 µm cutoff
1.5 to 2.2 µm stack
1.5 to 2.0 µm stack
1.5 to 1.8 µm stack
402
404
406
408
410
412
ΔT1
ΔT2
ΔJdark1
ΔJdark2
1x10^-8
1x10^-9
1x10^-10
1x10^-11
1x10^-12
Jdark (A/cm^2)
150
160
170
180
190
200
210
220
230
Temperature (K)

Fig. 4

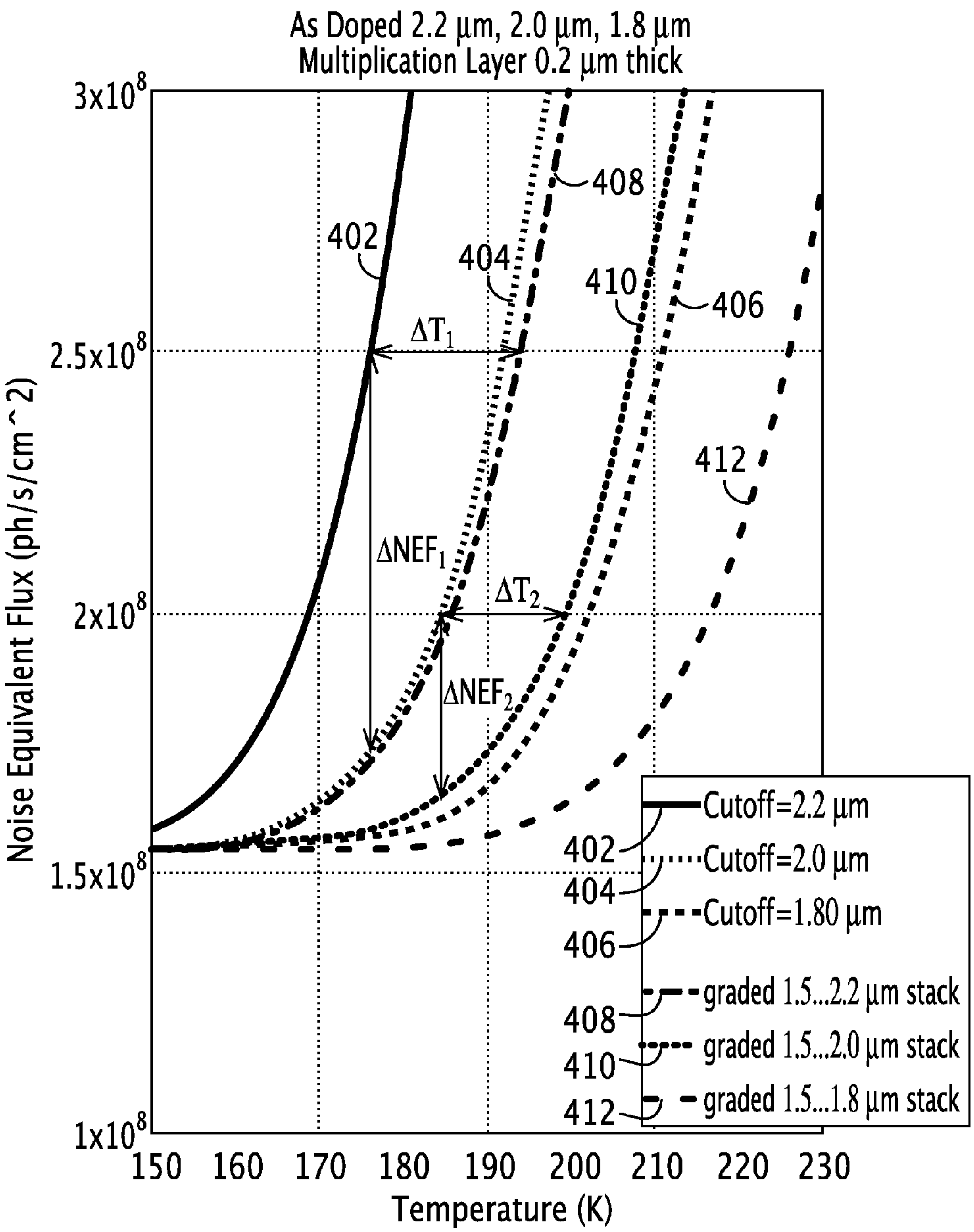

As Doped 2.2 µm, 2.0 µm, 1.8 µm
Multiplication Layer 0.2 µm thick
3x10^8
2.5x10^8
2x10^8
1.5x10^8
1x10^8
Noise Equivalent Flux (ph/s/cm^2)
150
160
170
180
190
200
210
220
230
Temperature (K)
402
404
408
410
406
412
ΔT1
ΔT2
ΔNEF1
ΔNEF2
Cutoff=2.2 µm
Cutoff=2.0 µm
Cutoff=1.80 µm
graded 1.5...2.2 µm stack
graded 1.5...2.0 µm stack
graded 1.5...1.8 µm stack

Fig. 5

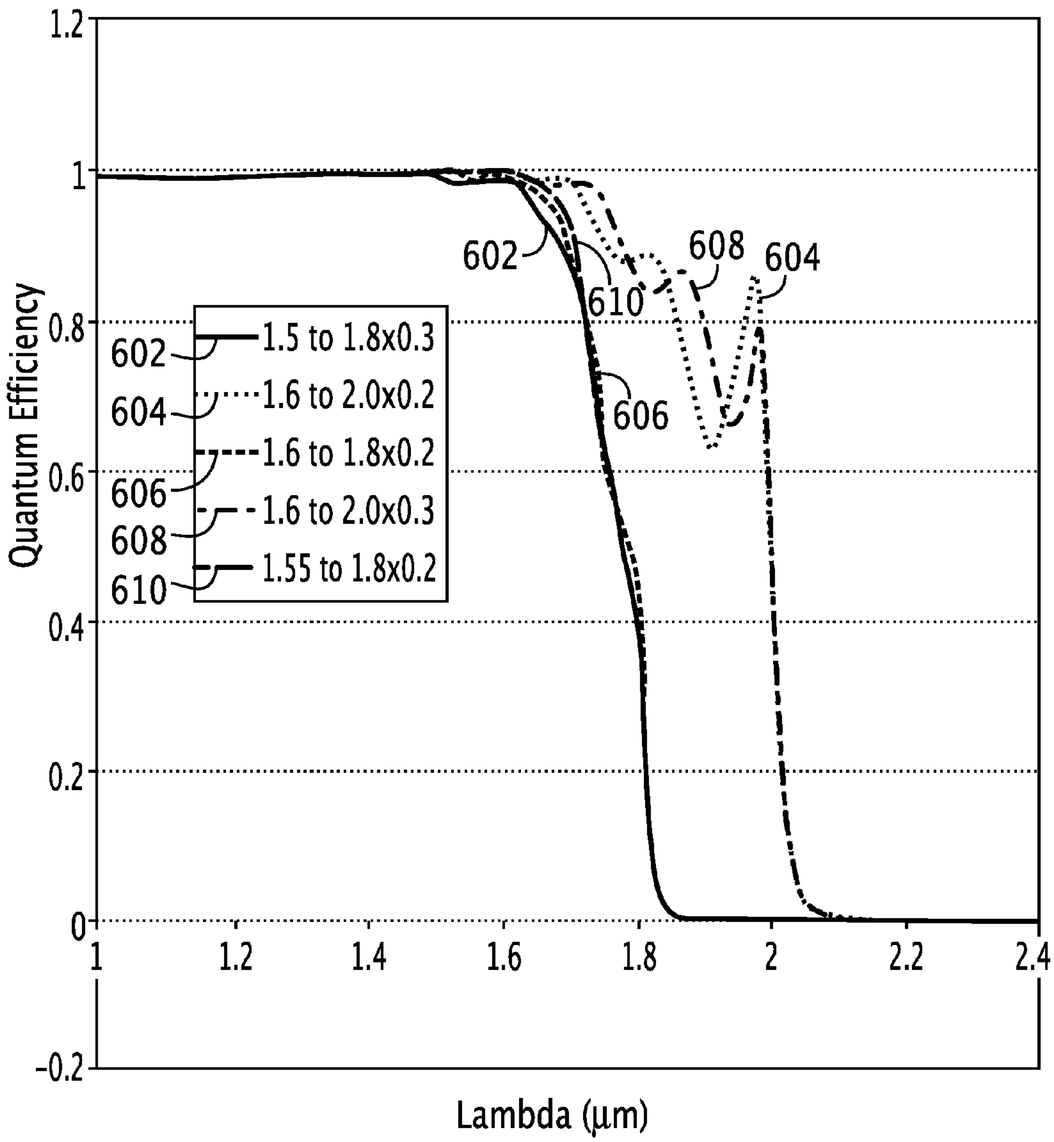

1.2
1
0.8
0.6
0.4
0.2
0
-0.2
Quantum Efficiency
1
1.2
1.4
1.6
1.8
2
2.2
2.4
Lambda (µm)
602
604
606
608
610
1.5 to 1.8x0.3
1.6 to 2.0x0.2
1.6 to 1.8x0.2
1.6 to 2.0x0.3
1.55 to 1.8x0.2

Fig. 6

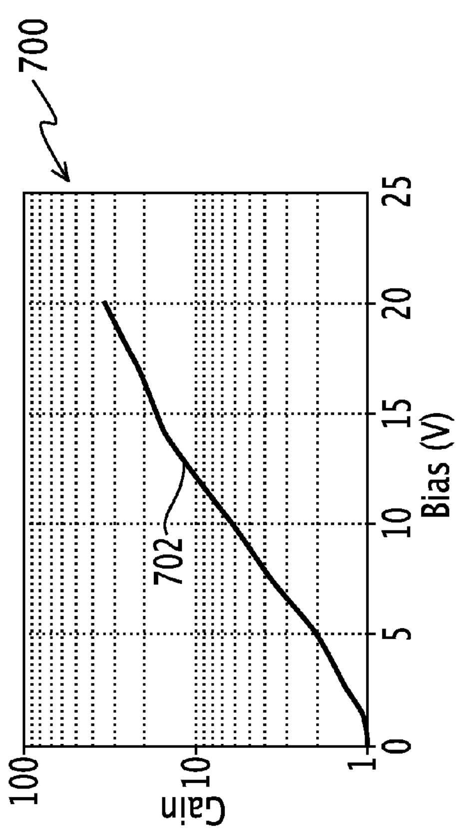


Fig. 7

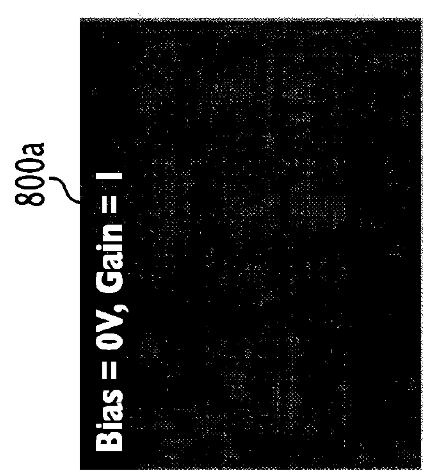


Fig. 8A

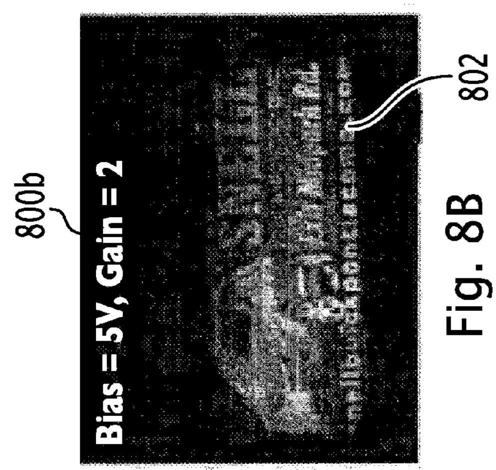


Fig. 8B

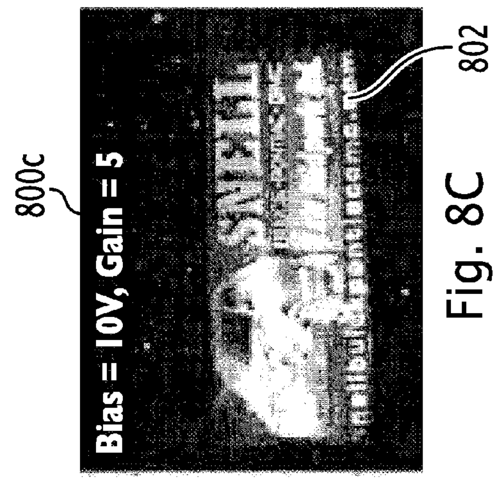


Fig. 8C

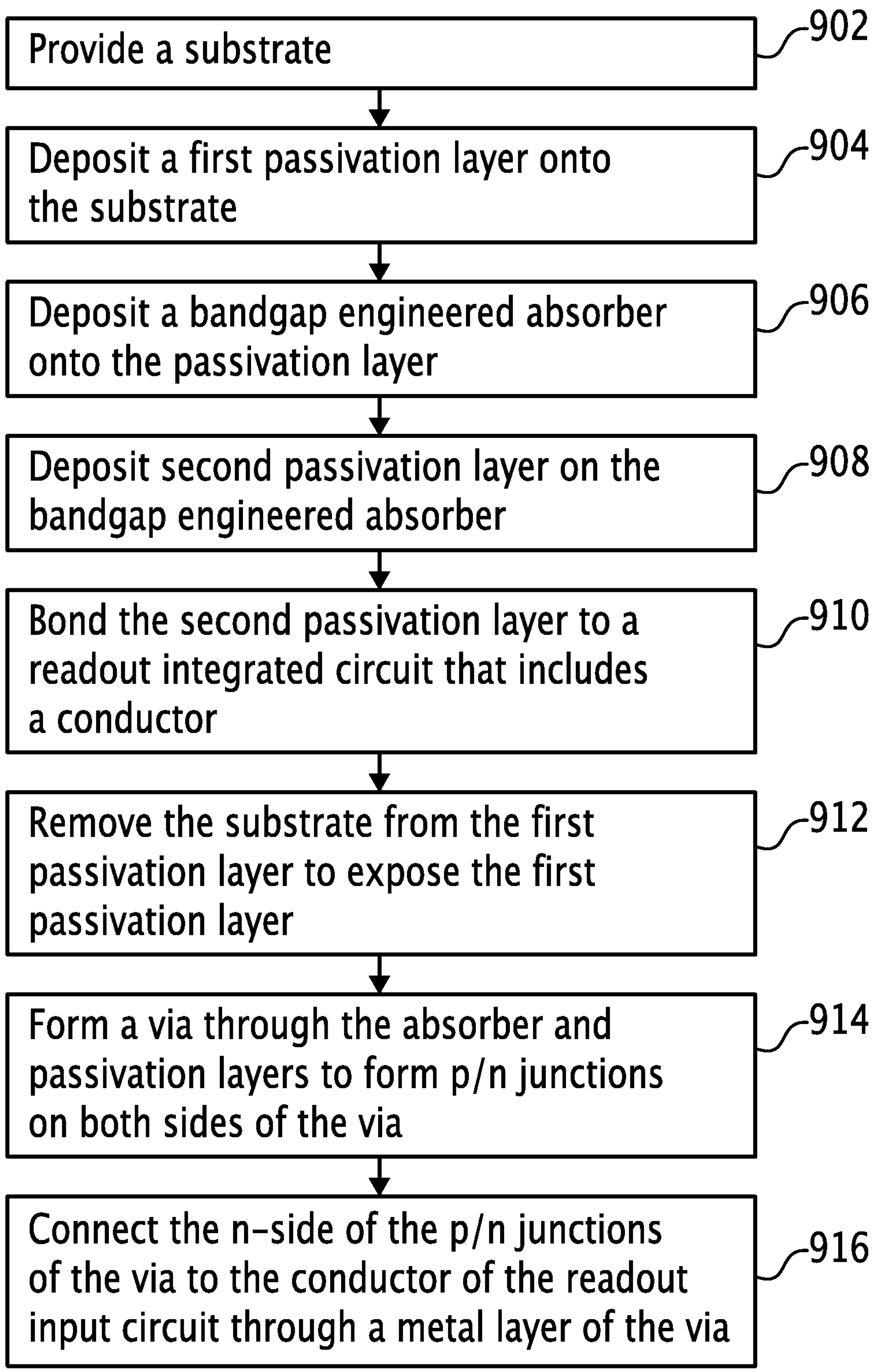

Provide a substrate
902
Deposit a first passivation layer onto the substrate
904
Deposit a bandgap engineered absorber onto the passivation layer
906
Deposit second passivation layer on the bandgap engineered absorber
908
Bond the second passivation layer to a readout integrated circuit that includes a conductor
910
Remove the substrate from the first passivation layer to expose the first passivation layer
912
Form a via through the absorber and passivation layers to form p/n junctions on both sides of the via
914
Connect the n-side of the p/n junctions of the via to the conductor of the readout input circuit through a metal layer of the via
916

Fig. 9

RADIATION DETECTOR HAVING A BANDGAP ENGINEERED ABSORBER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of U.S. patent application Ser. No. 12/853,174, filed Aug. 9, 2010, which is a non-provisional of U.S. Provisional Patent Application No. 61/232,510, filed Aug. 10, 2009, the disclosures of which are hereby incorporated in their entirety by reference for all purposes.

FIELD OF THE INVENTION

The principles of the present invention relate to imaging devices. More particularly, the principles of the present invention relate to a radiation detector, such as an infrared detector having a progressively graded bandgap or variable bandgap multilayer structure in which the detector's bandgap multilayer structure takes advantage of a longer cutoff region while minimizing the penalty associated with the added dark current of the longer cutoff region by confining this region to a thin layer within the graded or multilayer structure.

BACKGROUND OF THE INVENTION

Photodiodes have been configured in many ways and use many different materials for absorbing light energy over different wavelengths to generate photocurrent or voltage depending upon the mode. Temperature affects dark current as higher temperature increases dark current and degrades the noise equivalent sensitivity of the device. To achieve increased sensitivity, temperature is typically reduced. To reduce temperature, however, more power is needed to cool the detector. In addition, the cooling systems are necessarily larger and more expensive.

High density vertically integrated photodiode (HDVIP®, a trademark of DRS Technologies, Inc.) architecture has been employed to form pixels in focal plane arrays (FPAs) used for an infrared radiation detection. Photodiodes formed in prior art HDVIP® infrared detectors typically are formed from a single homogenous semiconductor layer of Mercury Cadmium Telluride ("HgCdTe") to have a given wavelength cutoff. Such prior art infrared detectors employing photodiodes formed of HgCdTe are susceptible to noise due to thermally excited current carriers and dark current sources at high operating temperatures and, thus, require substantial cooling to reduce the operating temperature of the detector so as to correspondingly reduce the noise and dark current of the detector.

Therefore, there has always been a need for an infrared radiation detectors that operate at higher temperatures without degradation in performance.

SUMMARY OF THE INVENTION

In accordance with imaging devices consistent with the principles of the present invention, a radiation detector is provided including an improved photodiode. The photodiode may have a radiation absorber having a first surface upon which radiation is received into the absorber. The absorber may have multiple layers each formed from a semiconductor material, such as $Hg_{1-x}Cd_xTe$. A first of the layers may be formed of a homogenous composition of the semiconductor material to have a first predetermined wavelength cutoff (e.g., 2 microns for the SWIR band). A second of the layers may be

disposed over the first layer and beneath the first surface of the absorber. The second layer may have a graded composition structure of the semiconductor material such that the second layer has a wavelength cutoff that varies from a second predetermined wavelength cutoff (e.g., 1.5 microns for the SWIR band) to the first predetermined wavelength cutoff (e.g., 2 microns). The first layer of the absorber of the photodiode preferably has a thickness that is substantially small (e.g. 0.2 microns or less in the SWIR example). The first layer of the absorber of the photodiode may have a thickness that is less than 0.2 microns and the second graded composition layer of the absorber may have a thickness that is greater than 0.2 microns. The structure of the graded multilayer absorber may be such that the second graded layer has a progressively smaller bandgap than the first layer. As a result of the progressively decreasing bandgap layers, carriers that are generated in the semiconductor material in response to light at wavelengths at or below the respective predetermined wavelength cutoffs drift through each of the layers until reaching the first, thin layer of the absorber because of the decreasing bandgaps or increasing wavelength cutoffs (e.g., 1.5 μm, 1.8 μm, 2.0 μm, and 2.2 μm).

The n-type and p-type regions of the photodiode may be formed of the same graded multilayer material structure. In this implementation, a p-type region of the photodiode and the n-type region of the photodiode may have the identical layer structure.

In one implementation, the absorber of the photodiode may have a third layer disposed on the second layer and defining the first surface of the absorber. The third layer may be formed of a homogenous composition of $Hg_{1-x}Cd_xTe$ to have the second predetermined wavelength cutoff. The third layer has a third energy bandgap that is greater than the energy bandgap of the second layer such that (i) carriers generated by radiation absorbed in the third layer (e.g., radiation less than the second predetermined wavelength cutoff of 1.5 microns for the SWIR band) drift to the second graded layer and (ii) carriers generated by radiation absorbed in the second layer (e.g., radiation between the second predetermined wavelength cutoff of 1.5 microns and the first predetermined wavelength cutoff of 2.0 microns for the SWIR band) drift to the first layer having the narrowest bandgap of the three absorber layers.

One embodiment of a radiation detector may include a photodiode including a radiation absorber having a first surface upon which radiation is received into the absorber. The absorber may have multiple layers, where each layer is formed from a semiconductor material. A first of the layers may be formed to have a first predetermined wavelength cutoff, a second of the layers may be disposed over the first layer and beneath the first surface of the absorber. The second layer may have a graded composition structure of the semiconductor material such that the second layer has a wavelength cutoff that varies from a second predetermined wavelength cutoff to the first predetermined wavelength cutoff.

One embodiment of a method for sensing radiation may include receiving radiation by a first radiation absorption layer. In response to receiving the radiation by the first radiation absorption layer, photogenerated carriers may be generated. The composition gradient results in gradient in the bandgap that creates an electric field gradient which pushes photogenerated carriers towards the narrow bandgap layer. A signal representative of the photogenerated and drifted carriers may be output for measuring the sensed radiation. At low applied reverse bias voltages, such as at ≤0.2 V, it behaves like a standard gain=1 photodiode. At higher reverse bias voltages, such as ≥3 V for MWIR and ≥6V, the n-type region begin to become depleted. The vertical drift of the photogenerated carriers makes the depleted narrow gap n-type region the region where avalanche multiplication occurs. Higher avalanche multiplication gains can thus be realized, as compared to a single homogeneous composition $Hg_{1-x}Cd_xTe$ absorber layer. The exact gain will depend on the applied bias and the composition of the narrow bandgap layer.

One embodiment of manufacturing a photodiode may include providing a substrate. A first passivation layer may be deposited or otherwise grown on the substrate. A bandgap engineered absorber may be deposited onto the passivation layer. A second passivation layer may be deposited onto the bandgap engineered absorber. The second passivation layer may be bonded onto a readout integrated circuit layer, where the readout integrated circuit includes a conductor. The substrate may be removed from the first passivation layer, thereby exposing the first passivation layer. A via may be formed through the absorber and passivation layers to form p/n-junctions on both sides of the via. The n-side of the p/n-junctions of the via may be connected to the conductor of the readout input circuit through a metal layer of the via.

Other devices, systems, methods, and features of the principles of the present invention will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate an implementation of the present invention and, together with the description, serve to explain the advantages and principles of the invention. In the drawings:

FIG. **1** depicts an exemplary graded multilayer material structure formed or as grown in accordance with the principles of the present invention for use in implementing a graded multilayer absorber of a photodiode (such as a high density vertically integrated photodiode (HDVIP®)), in a pixel **200** of an infrared radiation detector;

FIG. **2** depicts an exemplary pixel of an infrared radiation detector having a HDVIP® structure in which the photodiode of the pixel is formed to have an upside-down graded multilayer absorber shown in FIG. **1**;

FIG. **3** is a graph depicting illustrative progressively narrower bandgaps of the graded multilayer absorber of each of several photodiodes formed in accordance with the principles of the present invention;

FIG. **4** is a graph showing illustrative modeling results comparing variation in dark current density as a function of operating temperature for pixels having a HDVIP® structure with a photodiode having a single homogenous absorber layer of HgCdTe for a given wavelength cutoff versus pixels having a HDVIP® structure with a photodiode having a graded multilayer absorber structure of HgCdTe as shown in FIG. **2** graded to have a corresponding wavelength cutoff;

FIG. **5** is a graph showing illustrative modeling results comparing variation in noise equivalent flux or irradiance as a function of operating temperature for pixels having a HDVIP® structure with a photodiode having a single homogenous absorber layer of HgCdTe for a given wavelength cutoff versus pixels having a HDVIP® structure with a photodiode having a graded multilayer absorber structure of HgCdTe as shown in FIG. **2** graded to have a corresponding wavelength cutoff;

FIG. **6** is a graph depicting illustrative spectral responses in terms of relative quantum efficiency for various several photodiodes formed to have a graded multilayer absorber in accordance with the principles of the present invention;

FIG. **7** is a graph of an illustrative avalanche diode gain of a photodiode having a HDVIP® structure with a homogeneous absorber structure, where higher gain at the corresponding bias voltages are expected to be realized with a graded absorber structure in accordance with the principles of the present invention;

FIGS. **8**A-**8**C are images of an illustrative scene produced by three different operating conditions (e.g., three different bias voltages) in which an optical detector with absorber pixels having homogeneous absorber structures with the HDVIP® structure is set, where increased signal to noise ratio is expected to be realized with the HDVIP® structure with a graded absorber structure in accordance with the principles of the present invention; and

FIG. **9** is a flow diagram of an illustrative process for manufacturing a photodiode having a via, such as provided in the HDVIP® structure of FIG. **2**, with a bandgap engineered absorber, such as a graded multilayer absorber structure.

DETAILED DESCRIPTION OF THE INVENTION

A photodiode is an electronic sensor that converts radiation into current or voltage signals. Imaging devices, such as photodiodes, consistent with the principles of the present invention may provide an HDVIP® radiation detector with an improved photodiode structure as an alternative to the conventional HDVIP® radiation detectors with photodiodes formed using liquid phase epitaxy (LPE) to have a single homogenous semiconductor layer of $Hg_{1-x}Cd_xTe$ with a given wavelength cutoff. The improved photodiode structure of the HDVIP® radiation detector reduces dark current densities as compared to the conventional HDVIP® radiation detector or increases the operating temperature of each pixel employing the structure and the focal plane array (FPA) of pixels as a whole. In one embodiment, the photodiode structure incorporates a thin, narrow bandgap layer beneath a thicker, larger bandgap layer having a bandgap engineered absorber, such as a graded composition of $Hg_{1-x}Cd_xTe$. Carriers associated with the radiation absorbed in the graded layer drift to underlying narrower bandgap layers. The thin, narrow bandgap layer increases electronic avalanche photodiode (e-APD) gain on the detector at a given bias voltage as compared to the conventional HDVIP® detectors having the single homogenous semiconductor layer of $Hg_{1-x}Cd_xTe$, for example. It should be understood that alternative material and structure that provide for the functionality of the present invention may be utilized.

FIG. **1** depicts an exemplary graded multilayer material structure **100** formed in accordance with the principles of the present invention for use in implementing a graded multilayer absorber **204** of a photodiode **202**, such as a high density vertically integrated photodiode (HDVIP®), in a pixel **200** of an infrared radiation detector as shown in FIG. **2**. For clarity and brevity in the discussion to follow, the graded multilayer material structure **100** and the pixel **200** of the infrared radiation detector is described in reference to a specific example of a Short Wave Infrared detector (SWIR) that embodies the invention. However, the graded or multilayer material structure **100** is applicable to the Medium Wave Infrared (MWIR) and Long Wave Infrared (LWIR) bands and the formation of a MWIR or LWIR detector having a photodiode with a graded or multilayer absorber (or with p-type and n-type regions having the graded multilayer material structure **100**). Similarly, other components of the radiation detector shown in FIG. **2** besides the pixel **200** are not shown in the figures to avoid obscuring the principles of the present invention.

As shown in FIG. **1**, the graded or multilayer material structure **100** is formed on a substrate **50**. The substrate **50** may be of a material that has a lattice structure that matches lattice structure of the graded multilayer material structure **100**, which when formed, may be removed from the substrate **50** after the structure **100** is placed on a readout IC structure **208** of the pixels **200** that collectively form a focal plane array (FPA) of the radiation detector. In the implementation shown in FIG. **1**, the substrate **50** includes Cadmium Zinc Telluride ($Cd_{1-y}Zn_yTe$ or CZT), which has a lattice constant that matches the $Hg_{1-x}Cd_xTe$ material (also referenced as MCT) used in forming a wide energy bandgap passivation and buffer layer **102** as well as the bandgap layers **104**, **106**, and **108** of the graded multilayer material structure **100** used to implement the absorber **204** of the photodiode **202** in the pixel **200**. As understood in the art, the passivation and buffer layer **102** is used to protect absorption layers, such as bandgap layer **104**, and to prevent recombination of carriers, which reduces operating performance of the imaging device.

Initially, a buffer layer and a wide bandgap passivation layer **102** is grown on the substrate **50**. Note, each of the layers **102**, **104**, **106**, **108** and **110** of the graded multilayer material structure **100** may be grown using a known vapor phase epitaxy technique, such as molecular beam epitaxy (MBE) or metalorganic vapor phase epitaxy (MOVPE).

Next, to implement absorber **204** of photodiode **202** (FIG. **2**) for detecting wavelengths in the SWIR band, a homogenous layer **104** of $Hg_{x-1}Cd_xTe$ may be formed on the passivation and buffer layer **102** to have a thickness of approximately 1 μm. Although in this implementation of forming the graded multilayer material structure **100** the homogeneous layer **104** is deposited on the buffer layer **102** before the remaining layers **106** and **108**, the layer **104** represents the "third layer" in the stack of layers **108**, **106** and **104** of the photodiode **202** closest to the readout IC layer **208** (i.e., the graded multilayer structure **100** is placed upside-down on the readout IC layer **208**). When the graded multilayer material structure **100** is used to form the photodiode **202**, the layer **104** defines a first surface **210** of the absorber **204** upon which radiation is received into the absorber **204** of the photodiode **202**. Thus, in the implementation shown in FIGS. **1** and **2**, radiation is received and absorbed in the absorber layers **104**, **106** and **108** of the photodiode **202** in reverse order from the order in which the layers **104**, **106** and **108** are formed in the graded multilayer material structure **100**.

In one embodiment, the composition of Cd and Hg is set in the layer **104** so that the layer **104** has a wavelength cutoff of approximately 1.5 μm ("the predetermined wavelength cutoff"). Although each of the layers **104**, **106**, and **108** used to form the absorber **204** (e.g., p-type region in FIG. **2**) and the detection region (e.g., the n-type region in FIG. **2**) of the photodiode **202** is described as being formed of $Hg_{x-1}Cd_xTe$, each of the layers **104**, **106**, and **108** may be formed of another semiconductor material (such as PbSnTe, GaInSb or InGaAs) in which the composition of elements, including the semiconductor material, may be set so that the respective layer has a single predetermined wavelength cutoff for layers **104** and **108** (and corresponding bandgap) or a graded range of wavelength cutoffs (and corresponding graded bandgap range) for layer **106**, as further described in detail herein.

After the layer **104** is formed, a second layer **106** of $Hg_{x-1}Cd_xTe$ (or other semiconductor material) is disposed over or grown on the layer **104** to have a second thickness (e.g., 1.8 μm for the SWIR example) that is greater than the

thickness of the layer **104** and greater than the subsequent homogenous layer **108** of $Hg_{x-1}Cd_xTe$. Thus, most of photogeneration of the carriers would occur in wider bandgap $Hg_{1-x}Cd_xTe$ with lower dark current density. The second layer **106** may have a graded composition structure of $Hg_{x-1}Cd_xTe$ (or other semiconductor material) such that the second layer **106** has a wavelength cutoff that varies from 1.5 μm (the "second predetermined wavelength cutoff") to 2.0 μm (the "first predetermined wavelength cutoff"). For example, the mole fraction (x) of Cd may vary from 0.662 to form the 1.5 μm wavelength cutoff to 0.536 to form the 2.0 μm wavelength cutoff for the SWIR band. In this example, the mole fraction (1−x) of Hg is correspondingly varied from 0.338 to form the 1.5 μm wavelength cutoff to 0.464 to form the 2.0 μm wavelength cutoff for the SWIR band.

As described above, the second absorber ranges between a first wavelength cutoff (e.g., 1.5 μm) and a second wavelength cutoff (e.g., 2.0 μm). The specific values of the wavelength cutoffs are set using the specific composition of the material used to form the second absorber layer **106**. In the case of using $Hg_{x-1}Cd_xTe$, a Cd to Hg ratio, which is generally known as the Cd mole fraction, is used to set and adjust the specific wavelength cutoff as the second layer **106** is grown. As an example, if the Cd mole fraction ranges from 0.6 to 0.4, the wavelength cutoff may range from 1.5 μm to 2.0 μm. It is understood that composition of semiconductor material can be closely controlled when growing the layers through use of a software program executing on a molecular beam epitaxy machine.

After the second graded layer **106** is formed, the homogenous layer **108** of $Hg_{x-1}Cd_xTe$ (or other semiconductor material) may be disposed over or grown on the graded layer **106** to have a thickness of 0.2 μm or less (the "first thickness") for the SWIR band that is less than the thickness of the graded layer **106**. In forming the layer **108**, the mole fraction of Cd (x) may be set so that the layer **108** has a wavelength cutoff of 2.0 μm (the "first predetermined wavelength cutoff") to substantially match the end of the cutoff range of the graded layer **106**, where substantially matching the cutoff range means to be within a few percentage points. The thickness of the layer **108** is set to be the thinnest layer in the stack of layers **104**, **106**, and **108** forming the n-type region **206** and the p-type region **204** (e.g., the absorber region) of the photodiode **202** to be formed as described below. The thickness of the thinnest layer **108** is optimized to a thickness that reflects a tradeoff between dark current at a desired temperature of operation and functionality of the photodiode **202**. The thickness of the thinnest layer **108** also provides for a multiplication region when the photodiode is biased up to operate as an electron avalanche photodiode.

In the example show in FIG. **1**, the combined thickness (d) of the graded multilayer absorber structure (i.e., layers **104**, **106** and **108** in this embodiment) is approximately 3 μm for the SWIR band. However, the combined thickness may be made thinner or thicker for SWIR and other bands (such as MWIR or LWIR bands) without departing from the principles of the present invention.

The graded multilayer absorber structure (i.e., layers **104**, **106** and **108** in this embodiment) may be doped with As at $(1-2)\times10^{16}\ cm^{-3}$ or other dopants such as Hg vacancy or copper, to form a p-type structure that may be used to subsequently form the photodiode **202** of the pixel **200** in the infrared radiation detector as shown in FIG. **2**. After doping, another passivation layer **110** of a wider energy bandgap of MCT so that the absorber structure is sandwiched between the passivation layers **102** and **110**.

In another implementation, the passivation layer **110** (or another layer of $Hg_{x-1}Cd_xTe$ not shown) that is formed over the thinnest layer **108** may formed to have a reverse graded wavelength cutoff with a progressively larger cutoff than the layer **108** in the absorber structure. That is, a reverse graded cutoff from 2.0 μm to 1.5 μm for the SWIR band may be formed over the layer **108** to further ensure that the photogenerated carriers held in the layer **108** are readout through the corresponding layer **104** in the n-region **206** of the photodiode **202**. Since the layer **108** is the thinnest layer in the n-region **206** and p-type absorber region **204**, the majority of photogenerated carrier multiplication (and corresponding gain) occurs in the layer **108** of the n-region **206** when the photodiode **202** is readout through the readout IC layer **208** as further described herein.

Turning to FIG. **2**, to form the HDVIP® structure with the photodiode **202** employing the graded multilayer absorber structure (e.g., layers **104**, **106** and **108**), the structure **100** is positioned over and bonded to a readout IC **208** such that absorber layer **108** having the narrowest bandgap as compared to the absorber layers **104** and **106** is closest to the readout IC layer **208**. The structure **100** may then be bonded to the readout IC layer **208** via an epoxy layer **212** or using another known bonding technique. The substrate **50** may then be subsequently removed from the structure **100**. An antireflection (AR) coating layer **220** may then be formed over the passivation layer **102**.

Next, a hole or via **214** may be formed through the structure **100** (and the absorber layers **104**, **106** and **108**) using a known mechanical or chemical etching technique to reach a conductor (not shown) of an input preamp **216** or other component in the pixel readout IC layer **208**. In the example shown in FIG. **2**, the etching step followed by an implant, such as with Boron, causes the p-typed (As doped) absorber layers **104**, **106** and **108** such that the area **206** surrounding the via **214** is converted to an n-type region. However, the graded multilayer material structure **100** otherwise remains unchanged such that the p-type absorber **204** of the photodiode **202** and the n-type region **206** each have the same plurality of $Hg_{x-1}Cd_xTe$ (or other semiconductor material) layers **104**, **106** and **108** with corresponding wavelength cutoffs as viewed from the top or first surface **210** of the p-type absorber **204** (i.e., 1.5 μm wavelength cutoff for layer **104**, 1.5 μm to 2.0 μm wavelength cutoff for graded layer **106**, and 2.0 μm wavelength cutoff for layer **108** for the SWIR band, where each of the cutoffs are approximate values).

After the etching step and the formation of the n-type absorber or region **206** (the "detection region") of the photodiode **202**, a metal layer **218** may then be formed in the via **214** to form a contact between the n-type detection region **206** of the photodiode **202** and the readout IC **208**.

In the HDVIP® radiation detector configuration shown in FIG. **2**, radiation incident on the surface **210** of the absorber **204** of the photodiode **202** with wavelengths less than 1.5 μm is absorbed in the absorber layer **104**. Radiation having wavelengths in the graded cutoff range (e.g., 1.5 μm to 2.0 μm) passes through the layer **104** and is absorbed in the second absorber layer **106**. Some radiation having wavelengths less than the cutoff of the first absorber layer **108** (e.g., 2.0 μm) may pass through the layers **104** and **106** and be absorbed in the absorber layer **108** closest to the readout IC layer **208**. The photogenerated carriers generated by radiation absorbed in the top or third absorber layer **104** drift or flow from the wider bandgap of the layer **104** to the narrower graded bandgap region of the second graded absorber layer **106** due to an electric field gradient. The photogenerated carriers generated in the graded absorber layer **106** and carriers drifting from the layer **104** continue to flow or drift from the wider graded bandgap of the layer **106** to the narrower bandgap of the layer **108**, where the carriers remain trapped until "detected" through the corresponding layer **108** in the n-region **206** of the photodiode **202** and readout to the readout IC **208** for the respective pixel **200** of the radiation detector.

To emphasize how the graded bandgap region operates, in the case of a homogeneous absorber layer, electrons that are generated drift to the metal layer **218** of the via **214**. The metal layer **218** conducts the carriers to the conductor of the input preamp **216**. By contrast, in response to applying a bias voltage to the graded bandgap structure, an electric field gradient is generated in the graded bandgap structure. Using graded bandgap with the electric field gradient causes carriers that are generated by the bandgap engineered absorber, layers **104**, **106**, and **108**, to be forced or drift both vertically through the graded bandgap to the thinnest bandgap layer **108** and horizontally to the metal layer **218** of the via **214**.

At high bias voltages for readout of the photodiode **202** in the e-APD mode, the gain multiplication occurs almost entirely in the narrowest bandgap n-region of the 2.0 μm cutoff absorber layer **108**. As described in the examples to follow, the graded structure of the absorber **204** and the n-region of the photodiode **202** provides the benefit of the HDVIP® architecture while achieving higher gain from the narrowest bandgap and longest cutoff region (e.g., the 2.0 μm cutoff absorber layer **108** for the SWIR band) while reducing dark current noise than prior art HDVIP® radiation detectors that utilize a single homogenous absorber and n-type region for the photodiode.

Turning to FIG. **3**, a graph is shown that depicts the progressively narrower bandgaps of the graded multilayer absorber structure of three photodiodes formed in accordance with the principles of the present invention, such as the photodiode **202** in FIG. **2**. In the implementation shown in FIG. **3**, for each of the three photodiodes **202**, the third absorber layer **104** defining the radiation incident surface **210** of the photodiode absorber **204** is formed to have a wavelength cutoff of 1.65 μm, which has a corresponding energy bandgap **302** of approximately 0.752 eV for the SWIR band.

In this implementation, the second absorber layer **106** of each of the three photodiodes **202** is formed to have a graded wavelength cutoff range from 1.65 μm to 1.8 μm, 2.0 μm, or 2.2 μm, respectively. Alternative cutoff ranges could be utilized as well. As shown in FIG. **3**, the energy bandgap **304** of the second graded layer **106** of each of the three photodiodes drops from approximately 0.752 eV to approximately 0.689 eV for the cutoff of 1.8 μm, approximately 0.620 eV for the cutoff of 2.0 μm, and approximately 0.564 eV for the cutoff of 2.2 μm.

Continuing with the example shown in FIG. **3** for the SWIR band, the first absorber layer **108** of each of the three photodiodes **202** is formed to have a wavelength cutoff and energy bandgap **306** that matches the end of the graded cutoff range of the second absorber layer **106** (i.e., 1.8 μm cutoff with corresponding bandgap of 0.689 eV, 2.0 μm cutoff with corresponding bandgap of 0.620 eV, or 2.2 μm cutoff with corresponding bandgap of 0.564 eV).

As shown in FIG. **3**, photodiodes **202** formed to have a graded multilayer absorber **204** (p-type region) and detection region **206** (n-type region) consistent with the principles of the present invention have corresponding progressively narrower bandgaps **302**, **304** and **306** that cause photogenerated carriers to drift or flow to the first layer **108** having the narrowest bandgap **306** and corresponding deepest level for readout to the readout IC **208**.

The third layer **104** in the stack of the absorber **204** may be formed as described herein to have a shorter wavelength cutoff (e.g., 1.5 μm) and a greater energy bandgap **302** (e.g., 0.827 eV corresponding to 1.5 μm). In this implementation, the second graded absorber layer **106** is formed to have a beginning wavelength cutoff and corresponding beginning bandgap **304** that matches that of the third absorber layer **104** so that the overall electrical field gradient of the bandgap **304** is increased so that the photogenerated carriers drift more rapidly to the narrow bandgap of the first absorber layer **108** of the respective photodiode **202**.

The properties of a photodiode **202** having a graded multilayer absorber architecture in accordance with the principles of the present invention may be observed in the comparison examples shown in FIGS. **4** and **5**. FIG. **4** is a graph depicting an illustrative variation in dark current density as a function of operating temperature for pixels having an HDVIP® structure with a photodiode having a single homogenous absorber layer of HgCdTe for a given wavelength cutoff versus pixels having an HDVIP® structure with a photodiode having a graded multilayer absorber structure of HgCdTe consistent with the photodiode **202** in the pixel **200** of the HDVIP® radiation detector described herein. Three HDVIP® radiation detectors having a photodiode (referenced as **402**, **404** and **406**) with a single homogenous p-type absorber region and n-type detection region of HgCdTe were modeled to have a thickness of 3 μm and a wavelength cutoff of 2.2 μm, 2.0 μm and 1.8 μm, respectively. Three HDVIP® radiation detectors having a photodiode (referenced as **408**, **410** and **412**) with a graded multilayer architecture consistent with the photodiode **202** were modeled with the absorber layers having a combined thickness of 3 μm. The photodiodes **408**, **410**, and **412** were each formed to have: (1) a third absorber layer **104** with a thickness of approximately 1 μm and a wavelength cutoff of 1.5 μm; (2) a graded absorber layer **106** to have a thickness of approximately 1.8 μm and a graded wavelength cutoff in the range of 1.5 μm to 2.2 μm, 2.0 μm or 1.8 μm, respectively; and (3) a first absorber layer **102** with a thickness of approximately 0.2 μm and a wavelength cutoff matching the end range (i.e., 1.5 μm to 2.2 μm, 2.0 μm or 1.8 μm) of the graded cutoff range of the graded absorber layer **106**.

As shown in FIG. **4**, at a given operating temperature, each of the photodiodes **408**, **410** and **412** having a graded multilayer architecture consistent with the photodiode **202** has a dark current noise that is significantly less than the comparative photodiode **402**, **404** and **406** having a single homogenous HgCdTe layer with a wavelength cutoff that matches the end of the graded cutoff of the photodiode **408**, **410** and **412**. For example, at an operating temperature of 200 Kelvin (K), the prior art photodiode **402** with a 2.2 μm wavelength cutoff has a dark current noise of approximately 1.7×10^{-9} A/cm^2 while the comparative photodiode **408** with a graded wavelength cutoff to a 2.2 μm has a significantly less dark current noise of approximately 1.5×10^{-10} A/cm^2.

In addition, as shown in FIG. **4**, each of the photodiodes **408**, **410** and **412** having a graded multilayer architecture consistent with the photodiode **202** is able to operate at a higher temperature than the comparative photodiode **402**, **404** and **406** having a single homogenous $Hg_{1-x}Cd_xTe$ layer for a given dark current noise. Stated another way, the comparative photodiodes **402**, **404** and **406** having a single homogenous HgCdTe layer require additional cooling than the photodiodes **408**, **410** and **412** having a graded multilayer architecture consistent with the photodiode **202** to achieve the same dark current noise. For example, to operate at a dark current noise level of 1.0×10^{-9} A/cm^2, the prior art photodiode **402** with a 2.2 μm wavelength cutoff must be cooled to approximately 195K while the comparative photodiode **408** with a graded wavelength cutoff to a 2.2 μm is able to operate at a significantly higher temperature of 216K, which is over 20K difference. As a result, a smaller, less costly imaging system may be construed using a photodiode configured using the principles of the present invention because the photodiode does not needs as much cooling.

As an example of the thermal and noise improvements though inclusion of the bandgap engineered absorber in the HDVIP® radiation absorber, a thermal difference ΔT_1 between the comparative photodiode **402** and comparative photodiode **408** is shown to be approximately 20K (185K versus 205K) to achieve the same dark current noise level of 6×10^{-9} A/cm^2. Also, a thermal difference ΔT_2 between the comparative photodiode **404** and comparative photodiode **410** is shown to be approximately 20K (185K versus 205K) to achieve the same dark current noise level of 6×10^{-9} A/cm^2. In addition, a dark current noise level difference $\Delta Jdark_1$ is shown to decrease by approximately 34×10^{-11} (i.e., approximately 4×10^{-10}-approximately 6×10^{-11}) at a temperature of approximately 186K. Also, a dark current noise level difference $\Delta Jdark_2$ is shown to decrease by approximately 8.2×10^{-11} (i.e., approximately 1×10^{-10}-approximately 1.8×10^{-11}) at a temperature of approximately 190K.

FIG. **5** is a graph depicting the variation in noise equivalent flux (or irradiance) as a function of operating temperature for the photodiodes **402**, **404** and **406** having a single homogenous HgCdTe layer versus the comparative photodiodes **408**, **410** and **412** having a graded multilayer structure of HgCdTe. As shown in FIG. **5**, for a given operating temperature, each of the photodiodes **408**, **410** and **412** with the graded multilayer structure has a significantly less noise equivalent irradiance (NEI, also referenced as noise equivalent flux) than the comparative photodiode **402**, **404** and **406** having a single homogenous HgCdTe layer. For example, to achieve NEI of 2.5×10^8 photons/sec/cm^2, a very high level of sensitivity that would permit imaging under night glow conditions in a moonless night, the photodiode **412** with the graded gap structure formed to have the graded cutoff range ending at 1.8 μm may be cooled to approximately 226K while the comparative photodiode **406** with the single homogenous HgCdTe layer at 1.8 μm requires further cooling to approximately 212K, a 14K difference, which is a considerable difference at these temperatures, as understood in the art.

As an example of the thermal and noise improvements though inclusion of the bandgap engineered absorber in the HDVIP® radiation absorber, a thermal difference ΔT_1 between the comparative photodiode **402** and comparative photodiode **408** is shown to be approximately 20K (i.e., approximately 175K versus approximately 195K) to achieve the same noise equivalent flux of 2.5×10^{-8} ph/s/cm^2. Also, a thermal difference ΔT_2 between the comparative photodiode **404** and comparative photodiode **410** is shown to be approximately 15K (i.e., approximately 185K versus 200K) to achieve the same noise equivalent flux of 2.0×10^{-8} ph/s/cm^2. In addition, a noise equivalent flux difference ΔNEF_1 is shown to decrease by approximately 0.75×10^{-11} (i.e., approximately 2.5×10^{-8}-approximately 1.75×10^{-8}) at a temperature of approximately 178K. Also, a noise equivalent flux difference ΔNEF_1 is shown to decrease by approximately 0.35×10^{-11} (i.e., approximately 2×10^{-8}-approximately 1.65×10^{-8}) at a temperature of approximately 186K.

As apparent from FIGS. **4** and **5**, the dark current density reduces further and the operating temperature increases further for a photodiode **408**, **410** and **412** having a graded bandgap structure and progressively lower cutoff HgCdTe for the wide bandgap layer **106** and a thinner graded gap absorber region **108**, both readily realized in grown HgCdTe.

FIG. **6** is a graph depicting the spectral response in terms of quantum efficiency (QE) for various several photodiodes formed to have a graded multilayer absorber in accordance with the present invention consistent with the photodiode **202** in FIG. **1** where the graded multilayer absorber **106** for each photodiode (referenced as **602-610** in FIG. **6**) for different cutoffs of the graded bandgap layer **106** and the 0.2 μm thick narrow bandgap layer **108**. The modeling includes standard antireflection coating layers of ZnS and SiO_2 but optimized for the 1.0-1.7 μm spectral band. The results, plotted in FIG. **6**, show that the average QE is greater than 99% and a minimum QE value of approximately 90% at 1.7 μm wavelengths.

For MWIR and LWIR applications, a mirror on the backside of the detector or on the ROIC enables high QE values while maintaining relatively thin absorber layer structures of 3 μm and 5 μm, respectively.

FIG. **7** is a graph of an illustrative gain **702** of a photodiode having an HDVIP® structure with a homogeneous absorber structure when configured to operate in an avalanche diode mode. It is expected that higher gain at the corresponding bias voltages are expected to be realized with the graded structure in accordance with the principles of the present invention. As understood in the art, a photodiode may be configured in an avalanche diode mode by increasing bias voltage being applied to the photodiode. In this case, the photodiode was measured at 160K on a 12.5 μm pitch 8×8 array of 2.2 μm cutoff diodes. As shown, the gain is shown to be around 100 at a bias voltage of approximately 9.5V. As with the performance improvements, including thermal and dark current density performance improvements, of the photodiode provided in FIG. **2** and illustrated in FIGS. **3-5** over a photodiode with an HDVIP structure having a homogenous layer, the photodiode with the HDVIP structure operating in an avalanche diode mode has the same or analogous performance improvements over a photodiode with an HDVIP structure having a homogenous layer.

FIGS. **8**A-**8**C are images of an illustrative scene produced by three different operating conditions (e.g., three different bias voltages) in which an optical detector with absorber pixels having homogeneous absorber structures with the HDVIP® structure is set. It is expected that increased sensitivity will be realized with the HDVIP® structure with a graded absorber structure in accordance with the principles of the present invention. Each of the images were taken at night using the optical detector at different bias voltage levels. FIG. **8**A shows an image **800***a* taken using the optical detector with a bias voltage set to 0V, which translates to a gain of 1 by the photodiode. Hence, the image **800***a* is very dark. FIG. **8**B shows an image **800***b* taken using the optical detector with a bias voltage set to 5V, which translates to a gain of 2 by the photodiode. Hence, the image **800***b* shows improved contrast to see a sign **802**. FIG. **8**C shows an image **800***c* taken using the optical detector with a bias voltage set to 5V which translates to a gain of 5 by the photodiode. Hence, the image **800***c* is obtained at even greater sensitivity so that the sign **802** is more easily seen and the contrast in the image **800***c* is better than that of the image **800***b*.

FIG. **9** is a flow diagram of an illustrative process **900** for manufacturing a photodiode having a via, such as provided in the HDVIP structure of FIG. **2**, with a bandgap engineered absorber, such as a graded multilayer absorber structure as shown in FIG. **1**. The process **900** starts at step **902**, where a substrate may be provided. At step **904**, a first passivation layer may be deposited onto or grown on the substrate. The deposition may be performed by using vapor deposition or other deposition techniques, as understood in the art. At step **906**, a bandgap engineered absorber may be deposited onto the passivation layer. In one embodiment, the bandgap engineered absorber may include a non-homogenous layer, such as a graded absorption layer sandwiched between two homogeneous layers having different wavelength cutoffs, where the graded absorption layer may have a wavelength cutoff gradient ranging between the two different wavelength cutoffs of the respective two homogeneous layers. At step **908**, a second passivation layer may be deposited on the bandgap engineered absorber.

At step **910**, the second passivation layer may be bonded to a readout integrated circuit layer, where the readout integrated circuit may include a conductor. In one embodiment, epoxy may be used for bonding. The conductor may be used to conduct a current or voltage as a result of the carriers being generated and drifted through the bandgap engineered absorber to an external circuit for measuring radiation sensed by the photodiode, as understood in the art. At step **912**, the substrate may be removed from the first passivation layer to expose the first passivation layer. It should be understood that removal of the substrate may alternatively be removed prior to or after step **912**. At step **914**, a via may be formed through the absorber and passivation layers to form p/n junctions on both sides of the via. As understood in the art, a metal layer may be applied to walls of the via through a metalization process. At step **916**, the n-side of the p/n junctions of the via may be connected to the conductor of the readout input circuit through a metal layer of the via.

While various embodiments of the present invention have been described, it will be apparent to those of skill in the art that many more embodiments and implementations are possible that are within the scope of this invention. Accordingly, the present invention is not to be restricted except in light of the attached claims and their equivalents.

What is claimed is:

1. A method of making a photodiode, the method comprising:

forming a passivation layer on a substrate;

forming a first semiconductor layer on the passivation layer, the first semiconductor layer being characterized by a first wavelength cutoff;

forming a second semiconductor layer on the first semiconductor layer, the second semiconductor layer having a graded composition characterized by a wavelength cutoff that varies from the first wavelength cutoff to a second wavelength cutoff; and

removing the substrate from the passivation layer, thereby exposing the passivation layer.

2. The method of claim **1**, further comprising:

forming a third semiconductor layer on the second semiconductor layer, the third semiconductor layer being characterized by the second wavelength cutoff.

3. The method of claim **1**, wherein the first semiconductor layer and the second semiconductor layer each include at least one p-type region and at least one n-type region.

4. The method of claim **1**, further comprising:

forming a via through the passivation layer, the first semiconductor layer, and the second semiconductor layer; and

forming a metal layer on a wall of the via, the metal layer being in contact with the first semiconductor layer and the second semiconductor layer.

5. The method of claim **4**, further comprising:

doping the first semiconductor layer and the second semiconductor layer, thereby forming p/n-junctions on both sides of the via.

6. The method of claim 2, wherein the passivation layer is a first passivation layer, and wherein the method further comprises:

forming a second passivation layer on the third semiconductor layer.

7. The method of claim 6, further comprising:

bonding the second passivation layer to a readout integrated circuit layer, the readout integrated circuit layer comprising a conductor.

8. The method of claim 7, further comprising:

forming a metal layer that electrically couples the conductor to an n-type region of the first semiconductor layer and an n-type region of the second semiconductor layer.

9. The method of claim 8, wherein the readout integrated circuit layer comprises an input preamp electrically coupled to the conductor.

10. The method of claim 2, wherein the first semiconductor layer comprises a first homogenous layer of $Hg_{x-1}Cd_xTe$, wherein the second semiconductor layer comprises a non-homogeneous layer of $Hg_{x-1}Cd_xTe$, and wherein the third semiconductor layer comprises a second homogenous layer of $Hg_{x-1}Cd_xTe$.

11. The method of claim 2, wherein the third semiconductor layer is thinner than the first semiconductor layer.

12. The method of claim 1, wherein the second wavelength cutoff is higher than the first wavelength cutoff.

13. The method of claim 1, wherein the first semiconductor layer is characterized by a first bandgap, and wherein the second semiconductor layer is characterized by a bandgap that varies from the first bandgap to a second bandgap.

14. The method of claim 1, further comprising:

forming an anti-reflection coating on the passivation layer.

15. The method of claim 1, wherein a first thickness of the first semiconductor layer is about 0.2 microns or less.

16. The method of claim 15, wherein a second thickness of the second semiconductor layer is about 1.8 microns or greater.

17. The method of claim 1, wherein the passivation layer is formed on the first semiconductor layer using vapor deposition.

18. The method of claim 7, wherein the second passivation layer is bonded to the readout integrated circuit layer using epoxy.

19. The method of claim 4, wherein the via is formed using chemical or mechanical etching.

20. The method of claim 6, wherein the second passivation layer has a graded composition characterized by a wavelength cutoff that varies from the second wavelength cutoff to a third wavelength cutoff, the third wavelength cutoff being smaller than the second wavelength cutoff.

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